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Estimating the number of trees and forest area necessary to supply internationally traded volumes of big-leaf mahogany (*Swietenia macrophylla*) in Amazonia

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SUMMARY

Big-leaf mahogany's listing on CITES Appendix II requires producer nations to certify that exported supplies were obtained in a manner non-detrimental to the species' survival in its role in the ecosystem. Non-detriment findings based on annual export quotas should verify that current harvest rates are sustainable with respect to total commercial stocks. In order to assess this impact, a method for converting export-quality sawnwood volumes to numbers of standing trees is used to estimate the number of mahogany trees and forest area required to produce the original and revised 2007 export quotas set by Peru, correcting for systematic measurement error caused by buttresses and for stem defects caused by heart-rot (hollow bole). Based on large-scale inventory data from three forest sites in nearby south-west Brazil, the average commercial-sized (> 75 cm diameter in Peru) mahogany tree in this region would yield 6.4–8.5 m^3 of roundwood (standing volume), which in turn would be processed or milled into 1.7–2.2 m^3 of export-grade sawnwood. From this estimate, 6120–8070 commercial-sized trees would have been harvested to supply the original 2007 export quota of 13 477 m^3, from a forest area of 407 300–536 750 ha at landscape-scale densities reported by the Peruvian CITES Scientific Authority. To supply the revised export quota of 4983 m^3, an estimated 2260–2980 commercial-sized trees will be harvested from a forest area of 150 600–198 450 ha. Both estimates exceed the number of trees the Peruvian Scientific Authority estimates can be sustainably harvested annually (961 ± 144 trees > 75 cm diameter) based on preliminary inventory data. The method estimates that, since 1996, 154 000–203 000 mahogany trees have been logged in Peru from a forest area of 10.2–13.5 million ha to supply the total reported export volume during this period (including the revised 2007 export quota) of 339 114 m^3. This area corresponds to 18–25% of mahogany's total natural range in Peru, or 37–49% of mahogany's estimated remaining range in 2001. Without empirical knowledge of density patterns, surviving commercial stocks, and biological and technical issues linking processed lumber (sawnwood) to standing trees (roundwood), it will remain difficult to evaluate the sustainability of export quotas issued at the national level for mahogany or other tropical timber species.

Keywords: Amazon, Brazil, CITES Appendix II, export quota, non-detriment findings, Peru

INTRODUCTION

Natural populations of high-value tropical timber species face increasing pressure from logging and habitat loss across the New and Old World tropics, jeopardizing both commercial sustainability of trade and, in extreme cases, biological survival (Martini *et al.* 1994; Hall *et al.* 2003; Kometter *et al.* 2004). The most valuable widely traded Neotropical timber species, big-leaf mahogany (*Swietenia macrophylla*, Meliaceae) was listed on Appendix II of the Convention on International Trade in Endangered Species of Fauna and Flora (CITES) at the 12th Conference of Parties (CoP12) in 2002 in response to decades of overexploitation and widespread illegal logging, especially in the Amazon Basin (Rodan *et al.* 1992; Gullison *et al.* 1996; Snook 1996; Grogan *et al.* 2002; Blundell & Rodan 2003; Blundell 2004; Grogan & Barreto 2005). Mahogany is a canopy emergent tree capable of attaining heights of 45 m and above-buttress stem diameters of 2.5 m in Amazonia. It occurs across a vast crescent-shaped natural range in South America tracing seasonally dry tropical forests through Venezuela, Colombia, Ecuador, Peru, Brazil and Bolivia (Lamb 1966). Like most tropical trees, mahogany typically is present at low densities in primary (unlogged) forests, that is, < 1 commercial-sized tree (60–80 cm diameter depending on the country) ha^{-1} (Veríssimo *et al.* 1995; Gullison *et al.* 1996; Grogan *et al.* 2008). In south-west Amazonia, including Peru, it generally occurs at densities $\ll$0.1 ha^{-1} or much fewer than one tree in 10 ha at landscape scales (Kometter *et al.* 2004; Grogan *et al.* 2008).

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Mahogany has been logged in lowland south-west Amazonia since the 1920s (Hoy 1946; Lamb 1966). During the early decades, loggers exploited populations aggregated along the banks of mid-sized western tributaries of the Amazon River which could be felled directly into flowing water for transport to sawmills downstream, principally Iquitos in Peru and Manaus in Brazil. As these easily accessible populations were depleted, and as technology and overland transportation infrastructures improved, low-density *terra firme* populations came under increasing pressure during the 1970s and 1980s (White 1978; Grogan *et al.* 2002; Kometter *et al.* 2004). Today, intact commercial populations survive only in the most remote regions of south-west Amazonia such as in west Acre and south-west Amazonas (Brazil) and in the Alto Purús region of Peru (Grogan *et al.* 2002, 2008; Fagan & Shoobridge 2005, 2007).

Mahogany forms aboveground support roots or buttresses from an early age; these may reach 5 m or more up the lower bole on large trees (Lamb 1966; Grogan 2001). Heart-rot or hollow bole is also common in mahogany, responsible for high wastage rates during logging as sawyers speculatively fell even demonstrably hollow commercial-sized trees in hopes that some portion of the upper bole is merchantable (Veríssimo *et al.* 1995; Grogan *et al.* 2008).

Since November 2003, mahogany's listing on CITES Appendix II has required verification by producer nations that exported volumes of mahogany sawnwood were harvested legally and in a manner non-detrimental to the species' role in ecosystems where it naturally occurs. The concept of 'non-detriment' is generally understood to mean 'sustainably managed' (CITES 2003). Non-detriment findings (NDF) verifying sustainability of trade are made by the CITES Scientific Authority within each producer nation; the CITES Management Authority is responsible for verification of legal origin.

Scientific Authorities take two general approaches to NDF for timber species: (1) sustainability may be evaluated at the level of the production or management unit, based on knowledge of local population parameters such as density, population structure, growth and mortality rates, or (2) sustainability may be verified by setting annual export quotas based on empirical knowledge of national stocks, density patterns, population dynamics and long-term impacts of quota-driven exploitation rates (CITES 2003). At the Second Mahogany Working Group (MWG2) meeting in Belém (Brazil) in October 2003, Scientific Authority representatives from 14 of 17 Central and South American producer nations agreed that, in the absence of empirically sound national inventory data for mahogany, NDF should be made at the level of individual management units based on guidelines enumerated at MWG2 (CITES 2004). Since the Appendix II listing went into effect in November 2003, only one producer nation, Peru, has based NDF on national export quotas (NRDC [National Resources Defense Council] 2006).

Peru's use of export quotas for NDF has been controversial for several reasons. No export quota was set for 2004, the first year the Appendix II listing went into effect, and the 2005 quota (23 621 m^3) was based on the unsubstantiated assumption that export levels during previous years were sustainable (INRENA [Instituto Nacional de Recursos Naturales] 2005). Peru's Scientific Authority has repeatedly indicated that empirical knowledge of national mahogany stocks and other information necessary for making NDF based on export quotas is inadequate; an ITTO (International Tropical Timber Organization)-funded national inventory of Peruvian mahogany stocks is scheduled to be completed only in late 2007 (UNALM-FCF [Universidad Nacional Agraria La Molina, Facultad de Ciencias Forestales] 2004; Peru 2004, 2005). Peru's new (since 2001) concession system for forest management has not yet eliminated fraudulent industry nor corrupt regulatory practices (Schulte-Herbrüggen & Rossiter 2003; Fagan & Shoobridge 2005, 2007; Cerdan 2007; CITES 2007*a*). Finally, quantitative assumptions underlying export quotas have been questioned, especially that the 'average' commercial-sized mahogany tree from the Peruvian Amazon yields 8.4 m^3 of sawn timber for export (INRENA 2006*b*).

Based on separate visits to Peru in 2006 and 2007, the CITES Secretariat has recommended that 'export quotas should be based on sound, valid scientific information', and that to improve control over mahogany's exploitation, studies on the sawn lumber yield from logs should be undertaken (CITES 2006, 2007*a*). In June 2007, just prior to the 14th CoP in The Hague, the CITES Standing Committee required Peru to adjust the 2007 export quota for mahogany from 13 477 m^3 to 4983 m^3, the latter quantity representing timber obtained from forest concessions verified by field inspections to be in compliance with forest laws and regulations (CITES 2007*b*). Even so, the question of the sustainability of mahogany's exploitation in Peru has yet to be adequately addressed by export quotas.

In this paper we analyse a technical aspect of this controversy, namely the relationship between export quotas and the number of standing mahogany trees that must be logged to fill them. We describe how standing tree dimensions, principally stem diameter measured by forest inventory crews at 1.3 m height on the stem above ground (Brokaw & Thompson 2000), are used to estimate roundwood volume in cubic metres. We quantify the impact that two biological issues frequently associated with large timber trees in the tropics, namely aboveground buttresses or support roots and heart-rot creating hollow or defective boles, may have on roundwood estimation (Fig. 1). We discuss conversion efficiency when roundwood is processed or milled into sawn wood, and when export-grade sawnwood is subsequently selected for the international market. Finally, based on these data, we estimate the number of mahogany trees necessary to fill the original and revised 2007 export quotas from Peru, and to provide export volumes reported from Peru since the mid 1990s. These data in turn allow us to estimate the total forest area logged for mahogany during this period based on landscape-scale density data presented by the Peruvian Scientific Authority (UNALM-FCF 2007). We discuss implications of this analysis for the sustainability of international trade in mahogany from Peru.

Figure 1 Above: Measuring mahogany above buttresses in south-west Brazilian Amazonia. Below: Logged 135 cm diameter mahogany showing defective (hollow) base extending up the bole; no merchantable wood could be salvaged from this tree.

METHODS

Mahogany research and inventory sites

Field data on buttress and heart-rot incidence in mahogany are presented from seven long-term research and inventory sites across southern Amazonia in Brazil (Table 1). All sites were seasonally dry tropical forests, with < 2300 mm annual precipitation and a pronounced dry season lasting two to five months during which < 100 mm of rain falls per month. Soil origins and types ranged widely among sites, with coarser, more freely-draining nutrient-poor soils derived from Precambrian Brazilian Shield bedrock typical at south-eastern sites compared to finer, more water-retentive and nutrient-rich soils derived from Andean alluvium at south-western sites. Landscape physiography and forest structure and composition were similar at south-western sites to forests in Peru where mahogany occurs. In general, mahogany occurs at higher densities but achieves smaller stature in south-eastern forests compared to south-western forests (Grogan *et al.* 2008).

Relationship between stem diameter and buttress height

Long-term studies of tree diameter increment require replicable diameter measurements at fixed heights above buttresses. We describe the relationship between stem diameter and buttress height for 619 mahogany trees > 20 cm diameter monitored annually since 1997 or 2001 for diameter increment at five sites in south-east and south-west Brazilian Amazonia (Table 1). At all sites, diameter measurements were taken at 1.3 m height above ground or 30 cm above the reach of the tallest buttress at the time of first census.

Impact of buttresses on diameter measurements during forest inventories

We compared tree diameters registered by logging company inventory crews with diameters measured 30 cm above buttresses in long-term diameter increment studies. We consider measurement error to be the difference between recorded 'diameter at breast height' and diameter measured above buttresses for long-term increment studies.

Relationship between stem diameter and incidence of heart-rot (defect rate)

We field-checked all trees for hollow bases by tapping the stem on at least two sides with a mallet and judging whether the stem was solid by sound and feel. This test is commonly used by inventory crews to assess tree health; it cannot predict how far up the bole the defective core extends.

Converting stem diameter to roundwood volume

To estimate roundwood volume of standing trees we used a single-entry volume equation developed from over 300 plantation-grown mahogany trees in Sri Lanka (Mayhew & Newton 1998):

$$\text{roundwood volume}\,(\text{m}^3) = 0.056 - 0.01421(\text{D}) + 0.001036(\text{D2})$$

Table 1 Location of mahogany research (A) and simulation sites (B) in south-east (SE) and south-west (SW) Brazilian Amazonia. See Grogan *et al.* (2008) for detailed site descriptions.

Data	*Site*	*Region – State*	*Location*	*History of use*	*Area (ha)*
A	Marajoara	SE – Pará	7° 50′ S, 50° 16′ W	Logged	2050
A	Corral Redondo	SE – Pará	7° 42′ S, 50° 14′ W	Logged	600
A	Agua Azul	SE – Pará	6° 52′ S, 50° 32′ W	Logged	650
A	Pinkaití	SE – Pará	7° 41′ S, 51° 52′ W	Ecological Reserve	660
B	Faz. Imaculada II	SW – Rondônia	12° 43′ S, 61° 00′ W	Logged partially	1015
AB	Faz. São Jorge	SW – Acre	9° 25′ S, 68° 38′ W	Logging proposed	685
B	Faz. Seringal Novo Macapá	SW – Amazonas	8° 44′ S, 68° 59′ W	Logging proposed	11 370

where D = diameter at 1.3 m height or above buttresses. Roundwood estimates are increasingly uncertain for trees > 90 cm diameter since this was the upper diameter limit of sampled trees.

While double-entry equations (diameter plus commercial or total height) are available for mahogany, accurate height data are difficult and expensive to obtain in closed forest conditions, and are unavailable for most trees at sites in this study. For those trees with height data, volume estimates generated by the single-entry equation were similar to volume estimates generated by the best available double-entry equation for mahogany (Mayhew & Newton 1998).

Converting inventory diameter to roundwood volume

Stem diameters of commercial trees were adjusted at a fixed rate to account for observed systematic inventory measurement error due to buttresses. We further corrected estimated roundwood volumes according to a sliding scale derived from field observations, assuming that heart-rot or hollow stem incidence rises from 0% to 50% as trees grow from 60 cm to 150 cm diameter. While no statistically significant regression equation could be derived for this relationship from field data, this approach assumes an age component to heart-rot incidence, and is conservative (underestimates incidence) when compared with field observations. By this scale, 90% of trees 70–90 cm in diameter present fully merchantable boles. Thus, we assume that 10% of the estimated merchantable volume from trees in this size class must be discarded owing to heart-rot, with this percentage rising as trees grow larger.

Simulating mean per tree mahogany roundwood and sawnwood yields at three south-west Amazon sites

We used 100% inventory data from three sites in southwest Brazilian Amazonia (Table 1) to estimate harvest (roundwood) yields (m^3) per commercial tree according to current forest management regulations in Peru (90% harvest intensity of trees > 75 cm diameter). At all sites, physiography and forest structure and composition were similar to forests in Peru where mahogany occurs. Commercial populations at each site were 'logged' (resampled with replacement) 10 000 times to generate mean, 2.5 percentile, and 97.5 percentile roundwood yield estimates (the last two estimates representing 95% confidence intervals; Simon 1997; Resampling Stats, Inc. 2001). For comparative purposes, roundwood yields were estimated both from uncorrected tree diameters and volumes and from corrected diameters and volumes as described above.

Converting roundwood to sawnwood (processed) volume

Roundwood-to-sawnwood conversion efficiency indicates the percentage of roundwood that is converted during milling to merchantable sawnwood. Most published studies of roundwood conversion efficiency in the tropics report wastage rates exceeding 50% (Table 2). While roundwood-to-sawnwood conversion efficiency in the Amazon is commonly

Table 2 Published studies of roundwood-to-sawnwood conversion effiency in the tropics.

Country or region	*Conversion efficiency (%)*	*Source*	*Observation*
Brazil, E Amazon	20	Gerwing & Uhl (1997)	Many species for export market
Brazil, E Amazon	36	Gerwing & Uhl (1997)	Many species for domestic market
Brazil, Amazon	38	Lentini *et al.* (2003)	1998 Amazon-wide production, all species
Brazil, Amazon	42	Lentini *et al.* (2005)	2004 Amazon-wide production, all species
Brazil, SE Amazon	45	Veríssimo *et al.* (1995)	For mahogany
Peru	35	R. Mancilla (unpublished data 2001)	
Ghana	43	Appiah *et al.* (1987)	For *Chlorophora excelsa*
Nigeria	43	Uzowulu *et al.* (2005)	For five species
Malaysia	57–60	Lee (1976)	From 24 mills
Australia	40	Armstrong *et al.* (2004)	For *Khaya senegalensis* (plantation)

32–42% (Gerwing & Uhl 1997; Lentini *et al.* 2003; 2005; J. Zweede, personal communication 2007), we used a rate of 52% in keeping with conversion efficiency expected for mahogany by the Peruvian Management Authority (INRENA 2005). Considering that sawmill processing technology in south-west Amazonia on average remains below industry standards (R. Mancilla, unpublished data presented at el Grupo de Trabajo sobre la Caoba, Santa Cruz, Bolivia, 3–5 October 2001; J. Grogan, personal observation 2003), and that significant quantities of sawn mahogany from Peru are processed *in situ* by the highly wasteful *cuartoneo* (quartering) technique using single or paired chainsaws (Fagan & Shoobridge 2005, 2007), we believe this conversion rate to be optimistic.

No data are available to indicate what percentage of processed mahogany sawnwood meets export (*primeira*) standards. One FSC (Forest Stewardship Council)-certified logging company in Brazil achieved 42% roundwood-to-sawnwood conversion efficiency for ipê (*Tabebuia* spp.), another high-value tropical timber currently facing high demand from the North American residential decking market; of this, 36% met export standards (i.e. 1 m^3 roundwood = 0.15 m^3 export-grade sawnwood; L. Sobral, personal communication 2007). Though little mahogany is currently processed in Brazil, an estimated 28–36% of roundwood met export standards during the 1980s and 1990s (Veríssimo *et al.* 1995; J.-C. Malinski, personal communication 2007). Sills *et al.* (2002) reported that 51% of mahogany sawn during 1997–1999 at one of the most efficient band sawmills in Belize met export standards. For present purposes, we assumed that 50% of processed mahogany in south-western Amazonia met export standards, or 26% of roundwood (half of 52%).

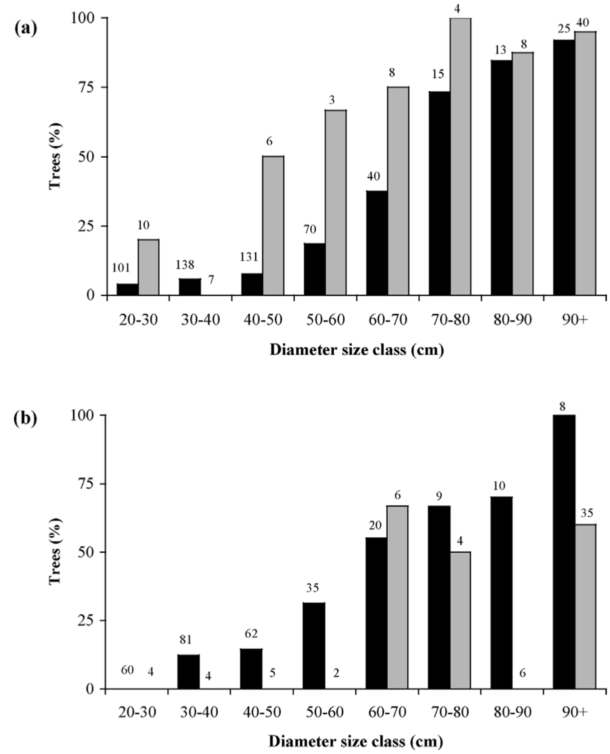

Figure 2 (*a*) Mahogany trees in south-east Amazonia (black fill) and south-west Amazonia (grey fill) with buttresses rising > 130 cm height above ground by 10-cm diameter size class. (*b*) Mahogany trees with heartrot or hollow base, bars as in (*a*). Numbers above columns show sample numbers by size class.

Estimating the number of trees and forest area necessary to fill export quotas

From estimates of export-grade sawnwood yield per commercial tree, we calculated the number of trees at each of three simulation sites required to produce 4983 m^3 of sawnwood for export (the revised 2007 export quota for Peru; CITES 2007*b*), the forest area required to produce this quantity of sawnwood for export given observed commercial densities at each site, and the forest area required to produce this quantity of sawnwood for export given the best available estimate of landscape-scale density of mahogany in Peru (0.0167 trees ha^{-1}; UNALM-FCF 2007; see also Kometter *et al.* 2004). We calculated the total land area necessary to produce reported export volumes of mahogany from Peru since the mid 1990s based on this landscape-scale density estimate.

RESULTS

Relationships between stem diameter, buttress height, measurement error and heart-rot (defect) rate

Buttress heights rose steadily on the bole as mahogany trees grew in diameter, with significant positive correlation recorded from both south-east and south-west Amazon sites (Figs 2*a*, 3*a*). Overall, 88% of trees > 75 cm diameter, the minimum commercial size in Peru, had buttresses rising higher than the standard measurement height. Buttresses rose as high as 5.2 m on trees exceeding 90 cm diameter.

Inventory crew measurement errors overestimated diameters of nearly all trees > 60 cm diameter in both regions (Fig. 3*b*). The magnitude of overestimation tended to increase with tree size (and therefore buttress height), but this positive correlation was not significant for commercial-sized trees. Mean % measurement error was 10.1 ± 1.5% (one standard error) and 15.4 ± 2.2% at south-east and south-west sites, respectively (Table 3). Larger mean % measurement error at the unlogged south-west sites was likely owing to the number of very large trees with high buttresses compared to the post-logging inventory at the south-east site where few large trees survived the harvest (Grogan *et al.* 2008).

The incidence of heart-rot or basal defect rose as tree diameter increased. At both south-east and south-west Amazon sites, heart-rot incidence differed between trees > 60 cm diameter and trees < 60 cm diameter (SE: $\chi^2 = 139.3$, df = 3, $p < 0.001$; SW: $\chi^2 = 15.2$, df = 3, $p < 0.01$). Overall, 60% of trees > 60 cm diameter demonstrated evidence of hollow bases (Fig. 2*b*), while 67% of trees > 90 cm diameter were defective at the base.

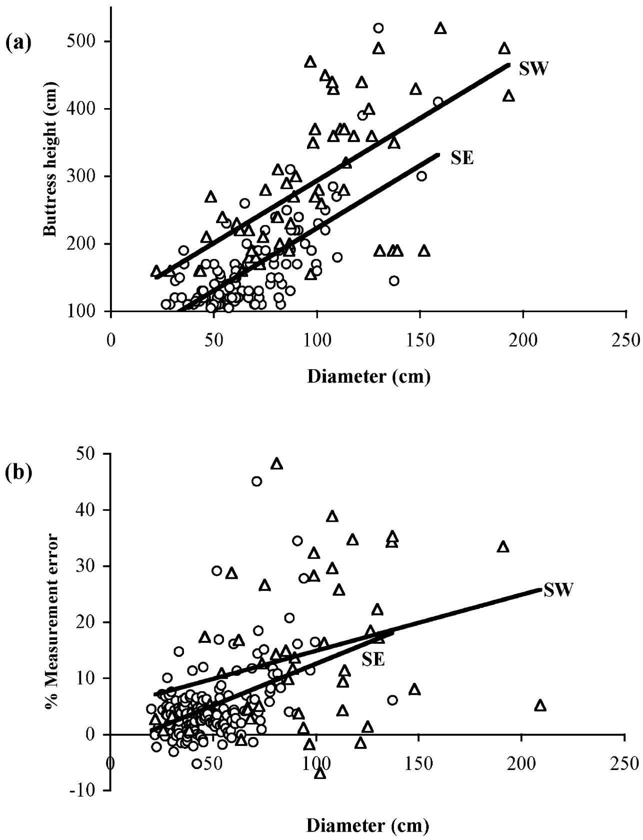

Figure 3 (*a*) Buttress height as a function of mahogany stem diameter in south-east (SE) Amazonia (circles) and south-west (SW) Amazonia (triangles). Trend lines show linear regressions for respective sites (SE, SW). (*b*) Inventory error as a function of stem diameter as in (*a*).

Table 3 % Measurement error in mahogany diameter measurements caused by buttresses, comparing forest inventory crew measurements versus actual above-buttress measurements of mahogany trees > 60 cm diameter in south-east and south-west Brazilian Amazonia. All median and mean error measures are positive (overestimates); SE = one standard error.

Region	*Median*	*Mean*	*SE*	*n*
South-east	7.5	10.1	1.5	39
South-west	13.2	15.4	2.2	38

Estimating roundwood volume from inventory data

The single-entry volume equation for mahogany (Mayhew & Newton 1998) estimates that 60 cm and 150 cm diameter trees yield 2.9 and 21.2 m^3 of roundwood, respectively (Table 4). After systematically reducing diameters by 10% due to inventory measurement error, and adjusting for defect rates from 0 to 50% on a sliding scale as trees grow larger, corrected volume estimates for 60 cm and 150 cm diameter trees were 2.3 and 8.5 m^3, respectively.

Correcting inventory data from three south-west Amazon sites by these criteria, and simulating logging (resampling 10 000 times) by current Peruvian legal standards at each site (10% retention of trees > 75 cm diameter), we estimate that the mean roundwood volume yield per tree would range from 6.4–8.5 m^3 among sites (Table 5). Corrected site-level roundwood volumes ranged from 48–57% of uncorrected volumes, with the lower value from the site (Amazonas) dominated by very large trees (higher defect rate affecting larger volume estimates).

Table 4 Volume estimates by size class for mahogany trees from 60–150 cm diameter: roundwood volume A from inventory data; roundwood volume B correcting volume A to account for 10% measurement error caused by buttresses; estimated defect rate by size class; roundwood volume C correcting volume B for defect rate.

Diameter (cm)	*Volume A (m^3)*	*Volume B (m^3)*	*Defect rate (%)*	*Volume C (m^3)*
60	2.9	2.3	0	2.3
70	4.1	3.3	10	2.9
80	5.5	4.4	10	4.0
90	7.2	5.7	20	4.6
100	9.0	7.2	20	5.7
110	11.0	8.8	30	6.2
120	13.3	10.6	30	7.4
130	15.7	12.6	40	7.5
140	18.4	14.7	40	8.8
150	21.2	17.0	50	8.5

Converting roundwood volume to export-grade sawnwood

Applying the 26% conversion efficiency rate, we estimate that mean sawnwood volume yield per tree for export would range from 1.7–2.2 m^3 among these three sites (Table 5).

The number of trees and forest area necessary to produce export quotas

At these per tree yield rates and based on observed commercial population densities at three south-west Amazon sites (0.025–0.113 trees > 75 cm diameter ha^{-1}), we estimate that 2260–2980 commercial-sized trees would be harvested from forest areas of 29 250–98 950 ha at these sites to fill Peru's revised 2007 export quota for mahogany of 4983 m^3 (Table 5). In Peru, where reported landscape-scale densities are lower, the estimated forest area necessary to produce the 2007 export quota ranges from 150 600–198 450 ha based on commercial population structures observed in Brazil. We estimate that 6120–8070 commercial-sized trees would have been harvested to supply the original 2007 export quota of 13 477 m^3, from a forest area in Peru of 407 300–534 750 ha.

From these data, we estimate that to supply the total reported export volume from Peru since 1996 (including the 2007 export quota) of 339 114 m^3 (Table 6), 154 000–203 000

Table 5 Simulated roundwood and sawnwood yields from three sites in south-western Amazonia following current forest management regulations in Peru (90% harvest intensity of trees > 75 cm diameter). Forest area (ha) required to produce 2007 Peru export quota (4983 m^3) is estimated by observed inventory densities and by the best available landscape-scale density estimate of trees > 75 cm diameter in Peru (0.0167 trees ha^{-1}). Upper and lower confidence intervals (CI) at $\alpha = 0.05$.

	Corrected for 10% error and defect rate			*No correction*		
	Rondônia	*Acre*	*Amazonas*	*Rondônia*	*Acre*	*Amazonas*
Number of trees >75 cm diameter (*n*)	115	45	289	115	45	289
Density of trees >75 cm diameter (ha^{-1})	0.113	0.066	0.025	0.113	0.066	0.025
Roundwood yield (m^3)	668	308	2202	1179	597	4637
2.5% CI	634	273	2079	1082	491	4282
97.5% CI	702	347	2332	1280	715	5006
Roundwood yield (m^3 $tree^{-1}$)	6.4	7.5	8.5	11.3	14.6	17.8
2.5% CI	6.1	6.7	8.0	10.4	12.0	16.5
97.5% CI	6.8	8.5	9.0	12.3	17.4	19.3
Sawnwood (26%) yield (m^3 $tree^{-1}$)	1.7	2.0	2.2	2.9	3.8	4.6
2.5% CI	1.6	1.7	2.1	2.7	3.1	4.3
97.5% CI	1.8	2.2	2.3	3.2	4.5	5.0
Number of trees (*n*) for 4983 m^3	2983	2553	2263	1691	1316	1075
2.5% CI	2839	2263	2137	1558	1099	995
97.5% CI	3141	2881	2397	1843	1601	1164
Forest area (ha) at each site for 4983 m^3	29 252	43 176	98 940	16 580	22 259	46 978
2.5% CI	27 840	38 275	93 398	15 276	18 592	43 513
97.5% CI	30 808	48 724	104 762	18 070	27 077	50 869
Forest area (ha) in Peru for 4983 m^3	198 458	169 843	150 590	112 486	87 561	71 502
2.5% CI	188 880	150 565	142 154	103 640	73 135	66 228
97.5% CI	209 013	191 669	159 450	122 594	106 515	77 423

Table 6 Reported mahogany exports from Peru since 1996. Sources: 1996–1999, UNEP-WCMC CITES Trade Database, UNEP, World Conservation Monitoring Centre, Cambridge, UK; 2000–2007, INRENA (2005; 2006*a*, *b*), CITES (2007*b*).

Year	*Exports* (m^3)
1996	5 397
1997	10 553
1998	20 270
1999	41 611
2000	51 267
2001	32 843
2002	52 138
2003	42 406
2004	30 785
2005	23 621
2006	23 240
2007	4 983
Total	339 114

mahogany trees have been logged from a forest area of 10.2–13.5 million ha (Table 7). This area corresponds to 18–25% of mahogany's total natural range of 55 million ha in Peru, or 37–49% of mahogany's estimated remaining range in 2001 of 27.5 million ha (Kometter *et al.* 2004). These estimates do not account for illegal mahogany production exiting the country via extra-legal channels.

Table 7 Estimated number of trees and forest area (at 0.0167 trees ha^{-1}) necessary to produce reported mahogany exports from Peru since 1996 and 2001 based on estimated harvest and processed yields from three sites in south-west Brazilian Amazonia (see Table 5).

Period	*Area*	*Number of trees*	*Area (ha)*
Since 1996	Rondônia	202 993	13 505 881
	Acre	173 724	11 558 511
	Amazonas	154 031	10 248 246
Since 2001	Rondônia	125 715	8 364 299
	Acre	107 589	7 158 278
	Amazonas	95 393	6 346 821

DISCUSSION

Better estimates of the number of trees and forest area that must be logged to fill export quotas for any species can be achieved by improving the empirical basis of assumptions underlying them. For mahogany, inventory data systematically overestimate roundwood volume yields because tree diameters are distorted by buttresses and unmerchantable hollow trees are not discounted. Correcting inventory data from three sites in south-west Amazonia led to 43–52% less roundwood, on average, than anticipated by field data. At the Amazonas site described in this paper, these biological realities nearly unravelled the business plan of the Brazilian logging company attempting to harvest mahogany there in a legal and sustainable manner (L. R. Oliveira, personal communication 2007). For less scrupulous operations, systematic overestimation of roundwood volumes opens a gaping loophole through which large volumes of illegally and unsustainably logged mahogany freely pass (Grogan *et al.* 2002). Landscape-scale density patterns are also poorly understood for mahogany throughout its range, rendering regional extrapolations as we present here a precarious undertaking.

We readily acknowledge that our assumptions for roundwood-to-sawnwood conversion efficiency are open to question given that reliable data on processing efficiency in Peru are unavailable. In its original 2007 export quota determination for Peru, INRENA assumed a combined 67% conversion efficiency for mahogany (52% sawn commercial wood plus 15% longwood and shortwood; INRENA 2006*b*), that is, that $1\,m^3$ roundwood yielded $0.67\,m^3$ sawnwood, with no further adjustment made for below-export-grade product. We believe that our assumptions are more realistic, given the general state of sawmill technology in this region and the highly wasteful *in situ* milling practices commonly used to convert mahogany roundwood into rough planks that can be manually hauled out of remote forests (Fagan & Shoobridge 2005, 2007). At the Amazonas site in Brazil, a highly capitalized logging company using above-average sawmill technology achieved roundwood-to-sawnwood conversion efficiency for mahogany of 63%, with 60% of sawnwood meeting international standards ($1\,m^3$ roundwood yielded $0.38\,m^3$ export-grade sawnwood; L. R. Oliveira, personal communication 2007). We are confident that our estimates, which assume yield rates 12% lower than this ($1\,m^3$ roundwood $= 0.26\,m^3$ export-grade sawnwood), are reasonable and probably optimistic for the Peruvian logging sector as a whole.

Our analysis indicates that the Peruvian logging industry will harvest 2260–2980 mahogany trees to fill the 2007 export quota of $4983\,m^3$. The number of trees necessary to fill the original 2007 quota of $13\,477\,m^3$ (INRENA 2006*b*) would have been 6120–8070. Under either quota, far more trees must be harvested than the Peruvian Scientific Authority has indicated can be sustainably logged annually based on preliminary inventory data (961 ± 144 trees > 75 cm diameter, or 549 ± 82 trees > 120 cm diameter; UNALM-FCF 2007). Furthermore, no empirical basis for evaluating the sustainability of these or any other harvest rates has been provided by Peruvian CITES Authorities.

Based on structured interviews with industry, academic and government experts, Kometter *et al.* (2004) concluded that 50% of mahogany's 55 million ha natural range in Peru had been commercially exhausted by 2001. Habitat loss and selective logging had further reduced mahogany densities across an additional 42% of this range, leaving 4.4 million ha unlogged. Respondents indicated that, barring significant changes in industry practices, mahogany would be commercially exhausted across 78% of its natural range within 10 years. Considering only export data since 2001, and including the current 2007 export quota ($210\,016\,m^3$ total; Table 7), we estimate that an additional 6.3–8.4 million ha have been exploited for mahogany since the Kometter *et al.* (2004) survey. Because mahogany density patterns are poorly understood and vary widely (Kometter *et al.* 2004; Grogan *et al.* 2008), it is difficult to know what portion of surviving commercial stocks these estimates represent. We believe that the Peruvian logging industry is likely approaching the end of legally harvestable mahogany stocks for two reasons: extensive illegal exploitation in the remote Alto Purús region (Fagan & Shoobridge 2005; 2007) indicates that more accessible stocks are severely depleted; and the sharp downward trend in export volumes since 2002 (Table 6) indicates that supply is waning.

Buttresses and heart-rot are not unique to mahogany. Many commercial timber species in the tropics form high buttresses, including *Cedrela* (Meliaceae, Spanish cedar or cedro), *Hymenolobium*, *Dinizia*, *Dipteryx* (Fabaceae, *angelim* and *cumarú*) and *Couratari* (Lecythidaceae, *tauarí*) in the Neotropics, *Entandrophragma* and *Khaya* (Meliaceae, African mahoganies) in central Africa, and *Shorea, Dipterocarpus* and *Dryobalanops* (Dipterocarpaceae, *meranti*, *keruing*, *kapur*) in south-east Asia. Heart-rot extensive enough to render commercial-sized trees unmerchantable typically affects 25–30% of harvestable trees in the Amazon (Holmes *et al.* 2002; Valle *et al.* 2006; J. Zweede, unpublished data 2007). Field data similar to and improving on those presented here will be necessary to evaluate the impact of international trade on natural populations as logging and forest conversion threaten more and more species with commercial exhaustion.

We question whether non-detriment findings as required under CITES Appendix II can be adequately made for timber species by setting export quotas. Sustainable production occurs by definition at the level of individual trees and local populations within forest management units, and can only be evaluated through detailed field audits. In contrast, export quotas assume absolute knowledge of natural stocks and a shared commitment by a community of producers to transparent harvest and business practices. When the commodity in question grows wild and is particularly valuable to the logger-entrepreneur, export quotas will inevitably resemble an opportunity for abuse, or at least someone else's responsibility, to some portion of that community. Once that happens, it becomes too expensive to play by the rules and the race for the bottom is on.

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